EXPLANATION

Magnitude

0.0 - 2.9 **3.0 - 3.9** **4.0 - 4.9**

pre-1971
1971 – 1975
1976 – 1980
1981 – 1985
1986 – 1990
1991 – 1995

B **Cross section -** Sections are shown at 1:62,500 scale. Dashed box encloses earthquakes plotted on cross section

Powerplant - Color shows the year in which it went on-line. The plant is currently on-line.

Powerplant - Color shows the year in which it went on-line. The plant is currently off-line.

Faults

(Fault traces were digitized at 1:750,000 (Jennings, 1994) and may be mislocated by as much as 0.8 km (0.5 mi) when plotted on this map at 1:250,000. Fault traces are not intended for engineering or land-use purposes.)

Late Quaternary (displacement <700,000 yr)
Early Quaternary (displacement <1,600,000 yr)

MAP C - TIME-DEPENDENT SEISMICITY IN THE GEYSERS AREA

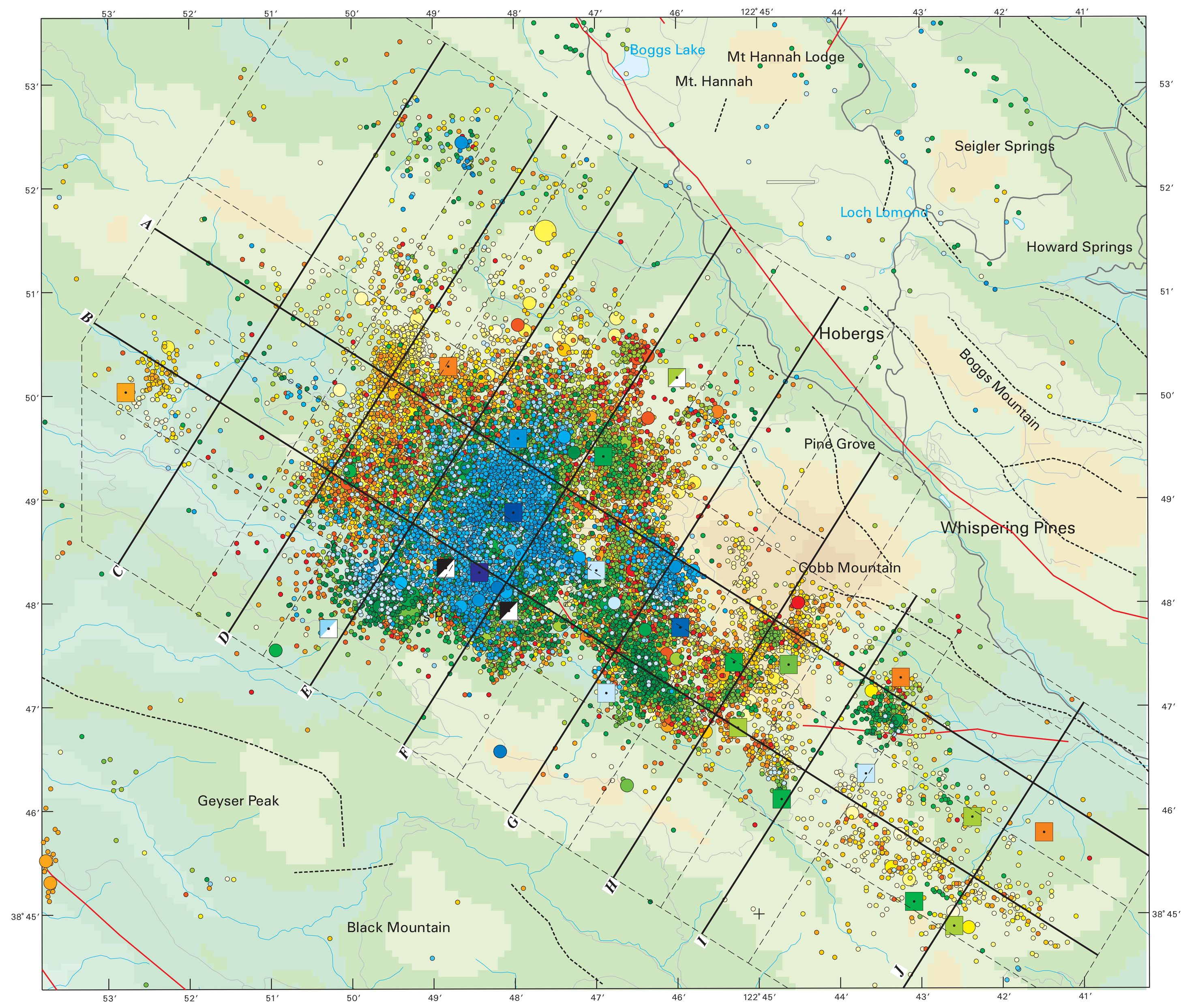
Map C and the associated cross sections provide a view of The Geysers seismicity at an expanded scale of 1:62,500 to portray the spatial detail of earthquake locations. The region corresponds to the area outlined on map B, and the data are identical. Unlike maps A and B, map C uses color to indicate the year when each earthquake occurred (see Explanation at left). The earliest occurring earthquakes are plotted last, which causes later earthquakes to be obscured. To reveal more fully the development of seismicity at The Geysers, we also plot the seismicity in a series of five, 5-year panels (at right) at a scale of 1:200,000. We show the locations of geothermal power plants operating at The Geysers steam field as rectangles. The time at which each power plant began producing electricity is also indicated by the color of the rectangle. Power plants that have ceased operation are shown by a split color scheme. The cross sections illustrate the same data as shown in map C and at the same scale. The convention for plotting the cross-sections is the same as described on map B. Locations of geothermal power plants are shown above the cross-sections. We omit earthquakes from the cross-section views whose depths are less than 0.25 km, as their locations are poorly determined.

There are few recorded earthquakes at The Geysers before 1975 when the U.S.G.S. commenced uniform seismic monitoring in the region. However, commercial steam production began in 1960, and water injection began in 1969. By the time seismic monitoring began, 10 power plants were already in operation. Only 5 rectangles are shown for these first 10 plants, because two plants occupy each of these sites. Although we do not show the location of wells supplying steam to a power plant or wells injecting steam condensate, they generally are located near the power plant.

Map C shows that the time at which seismicity is first observed generally coincides with the time at which power generating units began operation. Moreover, earthquakes occur only in the vicinity of the power plants. This correlation was first recognized by Eberhart-Phillips and Oppenheimer (1981). Oppenheimer (1986) then showed that the yearly volume of steam withdrawal since 1975 correlated with the number of earthquakes per year, suggesting that all the earthquake activity at The Geysers was induced. Stark (1992) demonstrated using proprietary seismic data that injection was responsible for inducing some of the seismicity in the field. It is possible, however, that stress perturbations due to reservoir contraction caused by heat and fluid withdrawal may also induce earthquakes.

Not only does seismicity appear following the commencement of geothermal power activities, but it apparently abates following the cessation of power production. Power Plant #15, located in the southwest region of the field, began producing power in 1979 and ceased operations in 1989. The seismicity depicted in the 5-year panels (at right) near this plant first shows earthquake activity in the 1981-1985 panel, but it is absent from the 1991-1995 panel.

The cross sections, like the map view, show that the seismicity does not occur on well defined faults. Instead seismicity indicates that failure occurs on small, unorganized faults or fractures in regions of production. Since the maximum depth of most wells does not exceed 3.5 km, the clusters of earthquakes at greater depths suggest that the source of some of the fluid withdrawal may be several kilometers below the wells. The lateral and vertical extent of seismicity is likely controlled by the boundaries of the volume of rock that yield commercially exploitable steam.



Topography from Defense Mapping Agency 1:250,000-scale Digital Elevation Model (DEM): Santa Rosa (east), 1987

Roads and hydrography from U.S. Geological Survey 1:100,000-scale Digital Line Graphs (DLG): Healdsburg, 1972

Geographic names from U.S. Geological Survey 1:100,000-scale published maps: Healdsburg, 1972

Transverse Mercator projection. Longitude of central meridian: 123°W.

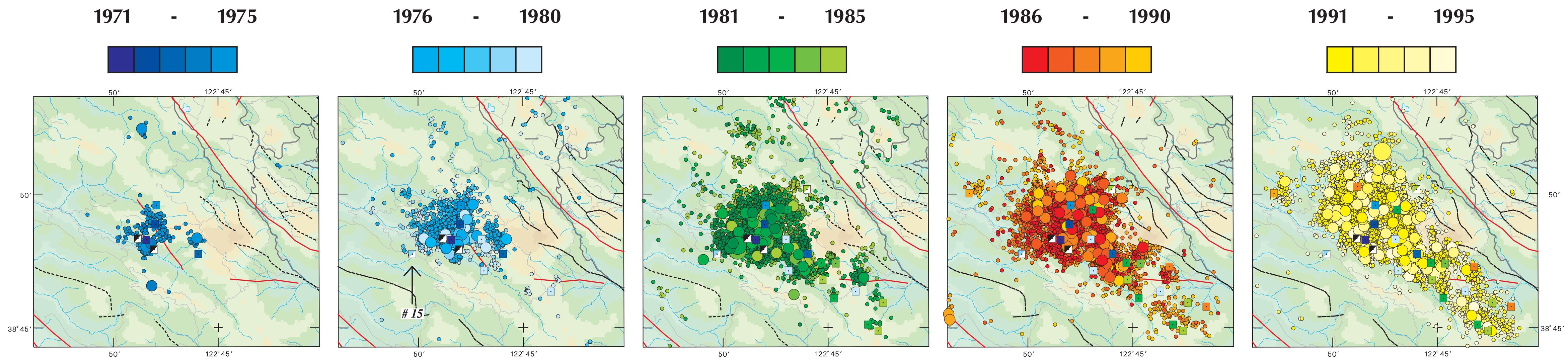
SCALE 1:62 500

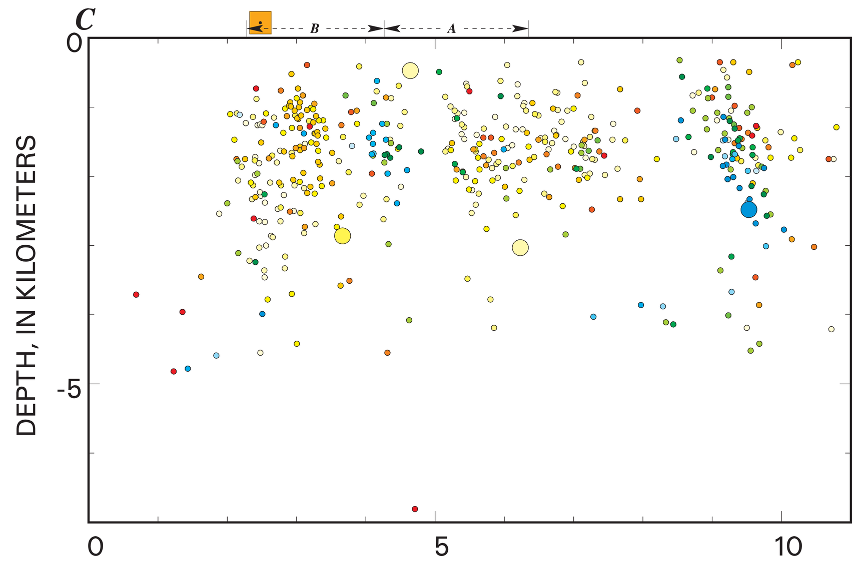
1 0 1 2 3 4 5 Statute Miles

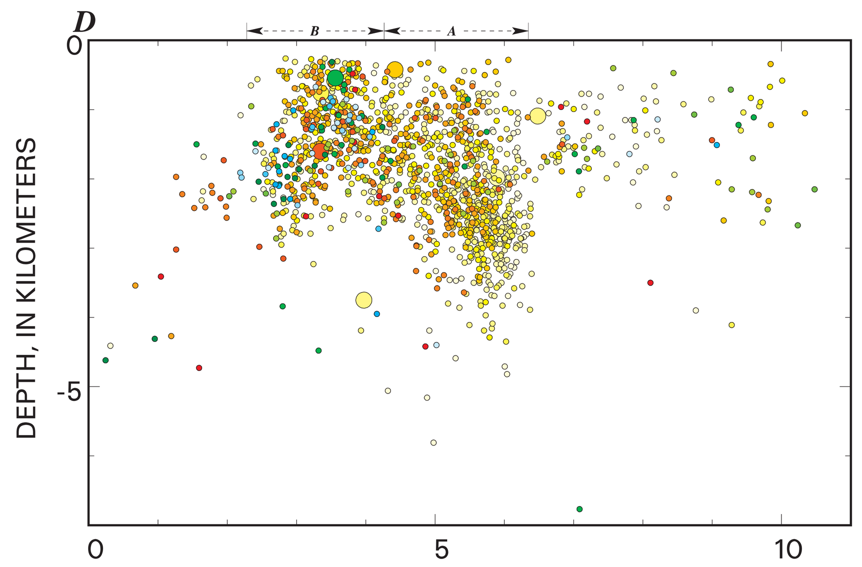
1 0 1 2 3 4 5 Kilometers

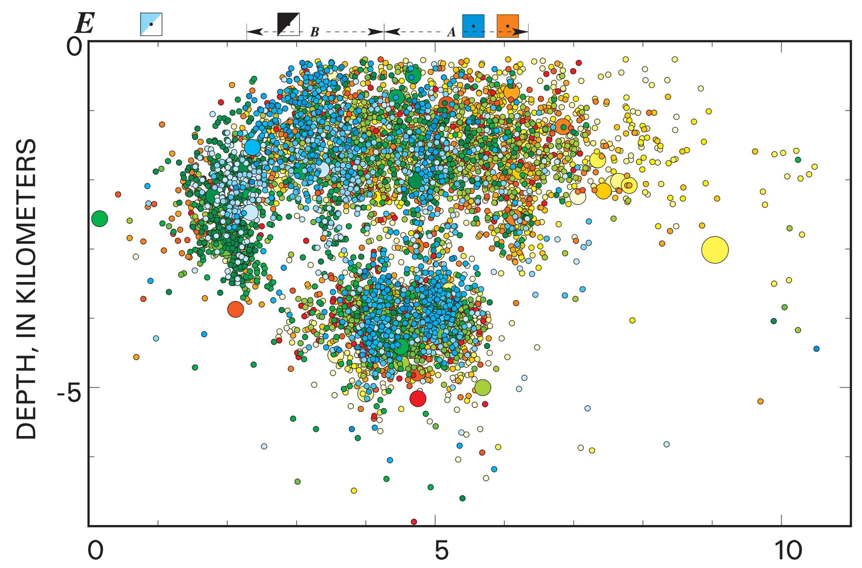
ELEVATION IN METERS

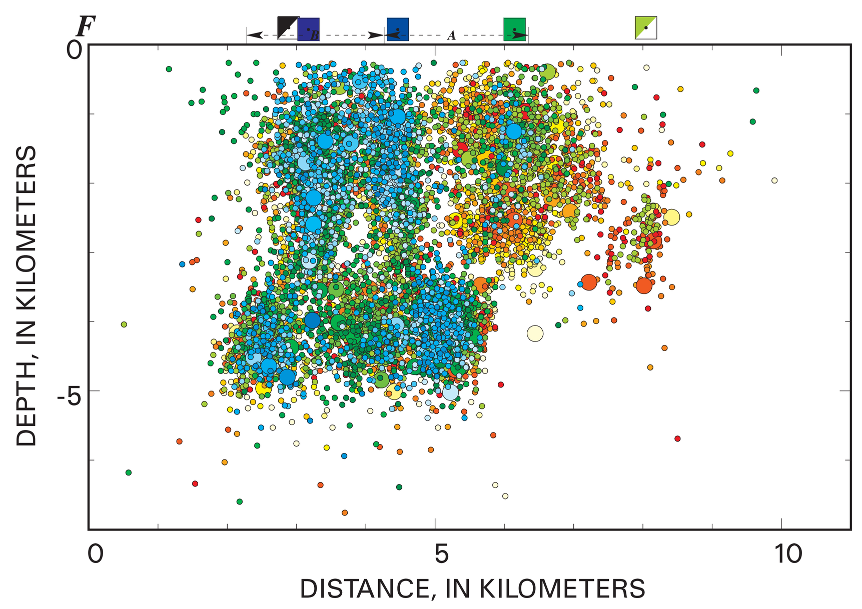
0 200 1000 2000 3000 4000

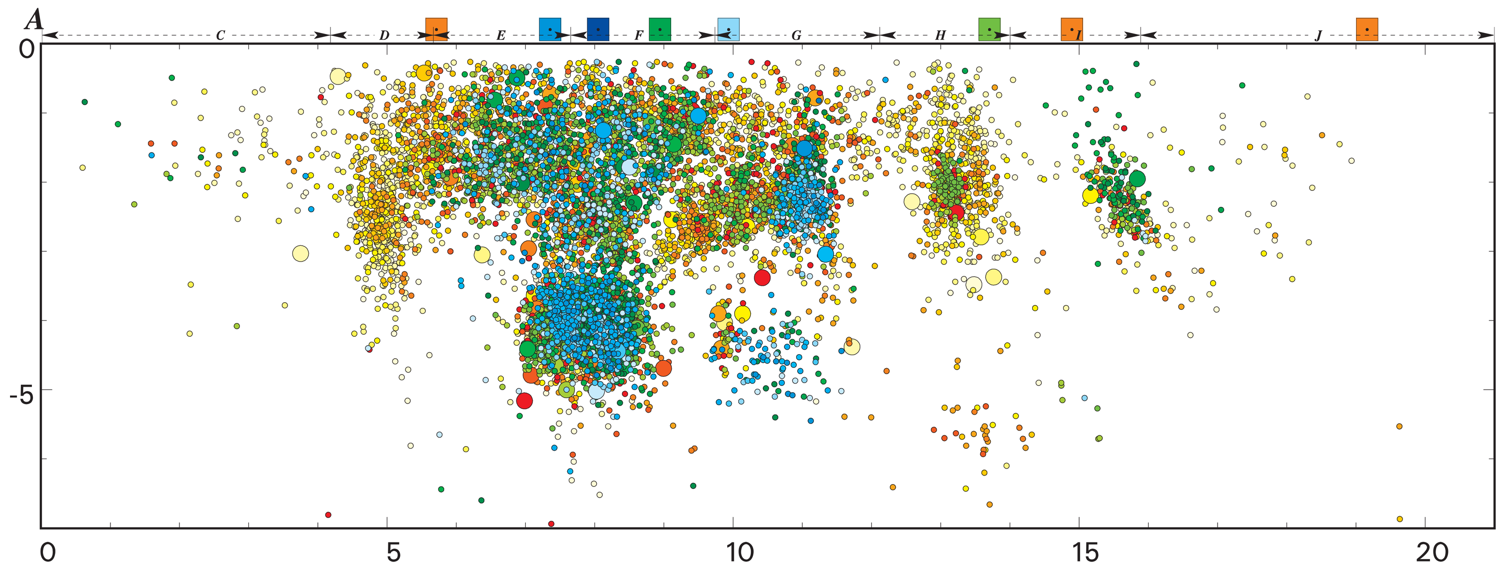


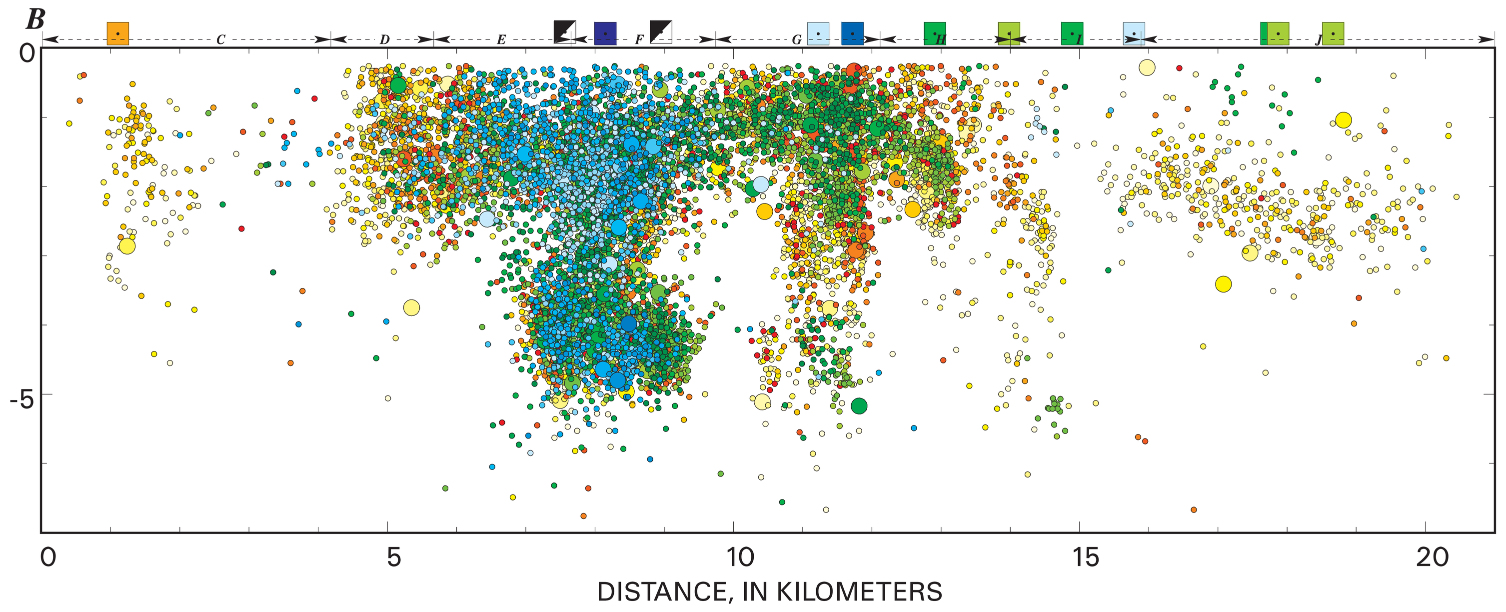


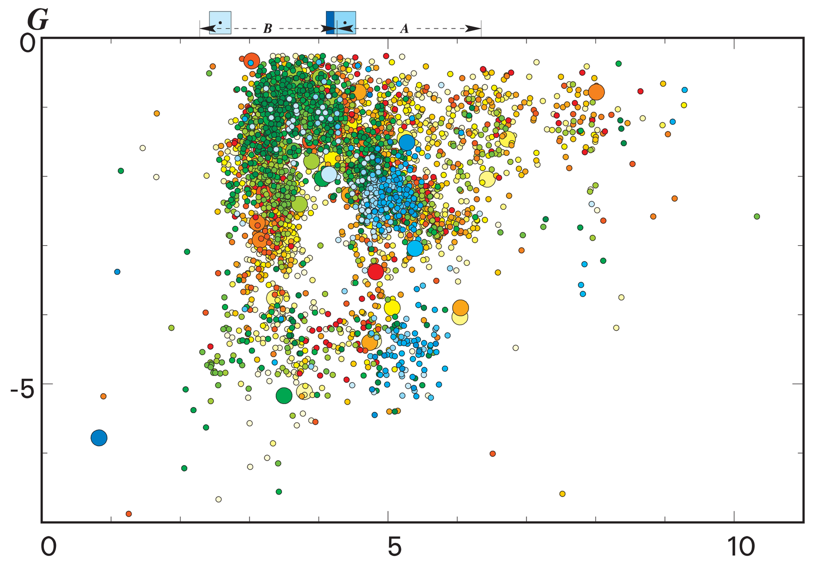


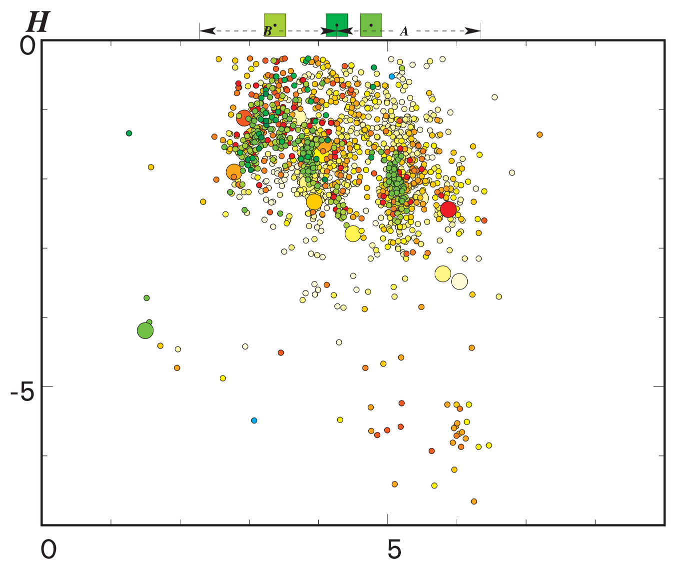


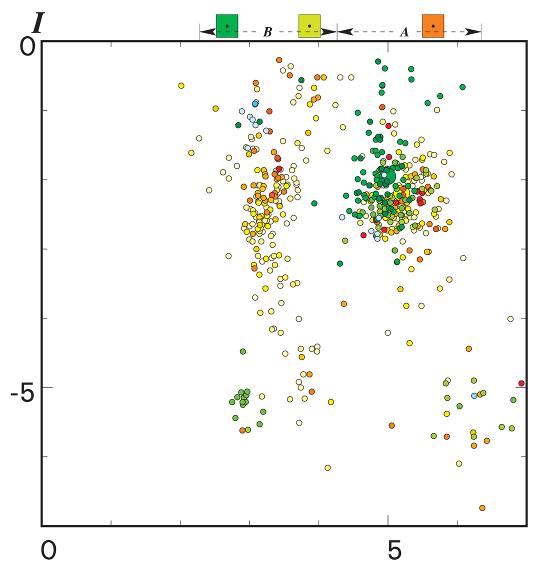


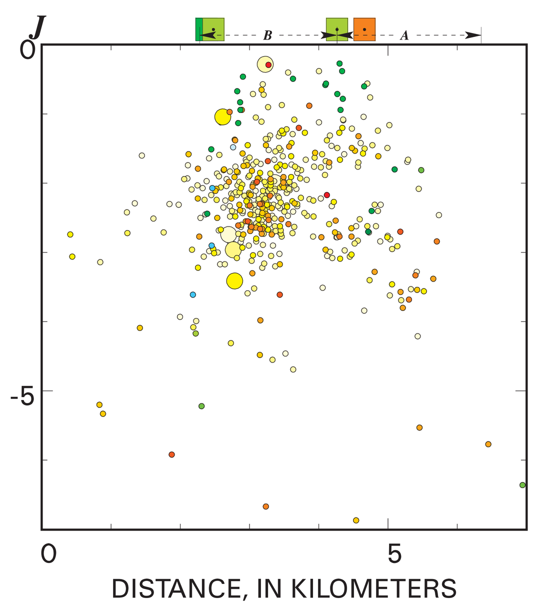










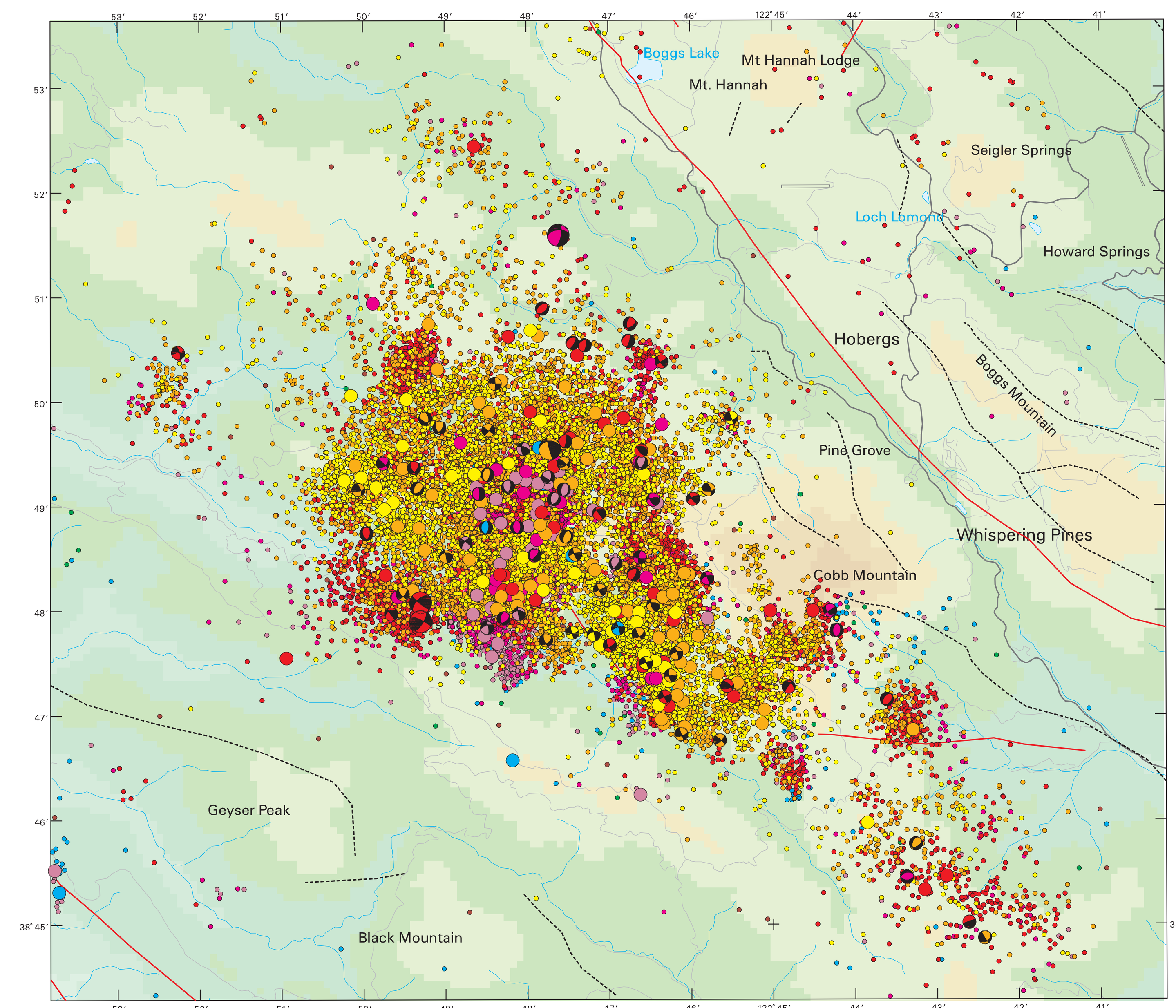


MAP D - DEPTH-DEPENDENT SEISMICITY AT THE GEYSERS AREA

Map D provides an additional view of The Geysers seismicity at an expanded scale of 1:62,500 to portray the depth dependence and focal mechanisms in more detail than can be shown on map A. The region corresponds to the rectangle outlined on maps A and B. The data and plotting conventions for earthquakes and focal mechanisms are identical to those described on sheet 1 for map A. However, the color scale reflects a depth interval of 0-7 km rather than 0-15 km (see Explanation beneath map).

Only four earthquakes larger than *M*4.0 have occurred in The Geysers field during the period 1975-1995. The largest quake, a *M*4.4, occurred on September 19, 199,2 north of the field in an area with little other earthquake activity. The USGS seismic network is able to locate all earthquakes above *M*1.2 at The Geysers, but routinely locates earthquakes smaller than *M*1.0. On average, 8 earthquakes per day are detected by the USGS seismic network at the Geysers, and about 3 earthquakes per day have a $M > 1.2$.

The 80 focal mechanisms exhibit a variety of fault orientations with slip ranging from strike-slip motion on vertical faults to normal slip on dipping faults. Because the seismicity occurs in a volume of apparently small faults or fractures, it is not possible to differentiate the slip plane from the auxiliary plane on the basis of comparisons with lineations in seismicity. Analysis of the focal mechanism data by Oppenheimer (1986) indicates the region is undergoing uniaxial extension with the axis of extension oriented near horizontal at approximately 105°. This axis is consistent with the orientation of the regional stress field, suggesting that the latter is the driving force for the earthquakes, but that the geothermal activities add incremental amounts of stress that induce small earthquakes.



Topography from Defense Mapping Agency 1:250,000-scale Digital Elevation Model (DEM): Santa Rosa (east), 1987

Roads and hydrography from U.S. Geological Survey 1:100,000-scale Digital Line Graphs (DLG): Healdsburg, 1972

Geographic names from U.S. Geological Survey 1:100,000-scale published maps: Healdsburg, 1972

Transverse Mercator projection. Longitude of central meridian: 123°W.

SCALE 1:62 500

1 0 1 2 3 4 5 Statute Miles

1 0 1 2 3 4 5 Kilometers

ELEVATION IN METERS

0 200 1000 2000 3000 4000

EXPLANATION

(Symbols shown on map are a combination of magnitude, depth, and focal mechanism (see page 1, figure 1) parameters)

Magnitude

0.0 - 2.9 **3.0 - 3.9** **4.0 - 4.9**

Depth, in kilometers

0 - 0.9 **1 - 1.9** **2.0 - 2.9** **3 - 3.9** **4.0 - 4.9** **5.0 - 5.9** **6.0 - 6.9** **7 +**

Faults

(Fault traces were digitized at 1:750,000 (Jennings, 1994) and may be mislocated by as much as 0.8 km (0.5 mi) when plotted on this map at 1:250,000. Fault traces are not intended for engineering or land-use purposes.)

Late Quaternary (displacement <700,000 yr)
Early Quaternary (displacement <1,600,000 yr)

SEISMICITY MAPS OF THE SANTA ROSA 1° × 2° QUADRANGLE, CALIFORNIA FOR THE PERIOD 1969-1995

by

Jeroen S. Preiss, Stephen R. Walter, and David H. Oppenheimer

2002

The publication also includes digital versions of the map sheets, which are available on the World Wide Web at: http://geopubs.wr.usgs.gov/open-file/of02-209.